

Role of generalized Ricci dark energy on chameleon field in the emergent universe

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In this paper, we have considered the generalized Ricci dark energy (GRDE) and generalized holographic dark energy (GHDE) in the scenario of emergent universe. Fractional energy density and deceleration parameters for GRDE were derived under emergent universe scenario. Also role of GRDE on the Chameleon field in the emergent universe scenario has been examined. Finally, the behaviours of the Chameleon scalar field ϕ , corresponding potential V and associated function f were investigated in presence of GRDE.

A. Introduction

The accelerated expansion of the universe has now been well documented in the literature [1] and is strongly confirmed by the cosmic microwave background radiation (CMBR) [2] and Sloan Digital Sky Survey (SDSS)[3]. Another way of presenting this kinematic property of the universe is to postulate the existence of a new entity dark energy (DE) that has been reviewed in several literatures [4]. Although observationally well-established, no single theoretical model provides an entirely compelling framework within which cosmic acceleration or DE can be understood. The simplest candidate of dark energy is the vacuum energy density or cosmological constant Λ , whose energy density remains constant with time $\rho_\Lambda = \Lambda/8\pi G$ and whose equation of motion is also fixed, $w = p_\Lambda/\rho_\Lambda = -1$ (p_Λ is the pressure) during the evolution of the universe. The resulting cosmological model, Λ CDM, consists of a mixture of vacuum energy and cold dark matter [5]. Another possibility is QCDM cosmologies based on a mixture of cold dark matter and quintessence ($-1 < w \leq 0$) [6]. Numerous other candidates for dark energy have also been proposed in the literature, such as an evolving canonical scalar field [7] usually referred to as quintessence, the phantom energy [8] with an equation of state smaller than -1 violating the weak energy condition, the quintom energy [9] with an equation of state evolving across -1 , and so forth.

In recent times, an interesting attempt for probing the nature of dark energy within the framework of quantum gravity is the so-called holographic dark energy (HDE) proposal [10]. The holographic principle is an important result of the recent research for exploring the quantum gravity [11]. This principle is enlightened by investigations of the quantum property of black holes [e.g. 12]. In a quantum gravity system, the conventional local quantum field theory will break down because it contains too many degrees of freedom that will lead to the formation of a black hole breaking the effectiveness of the quantum field theory [11]. The HDE model is constructed by considering the holographic principle and some features of the theory of quantum gravity. The HDE constructed in light of the holographic principle possesses some significant features of an underlying theory of dark energy [13]. According to the holographic principle, the number of degrees of freedom in a bounded system should be finite and has relations with the area of its boundary. The energy density of HDE is given by $\rho_\Lambda = 3c^2 M_{pl}^2 L^{-2}$ [14], where c is a numerical constant and $M_{pl} = 1/\sqrt{8\pi G}$ is the reduced Plank mass. If we take L as the size of the current Universe, for instance, the Hubble radius H^{-1} , then the dark energy density will be close to the observational result. This reflects that means that there is duality between UV cut-off and IR cut-off. The UV cut-off is related to the vacuum energy, and the IR cut-off is related to the large scale of the universe, for example the Hubble horizon, event horizon or particle horizon [14, 15].

Inspired by the holographic principle, Gao et al.[16] took the Ricci scalar as the IR cut-off and named it the Ricci dark energy (RDE), in which they take the Ricci scalar R as the IR cutoff. With proper choice of parameters the equation of state crosses -1 , so it is a quintom [13]. The Ricci scalar of FRW universe is given by $R = -6 \left(\dot{H} + 2H^2 + \frac{k}{a^2} \right)$, where H is the Hubble parameter, a is the scale factor and k is the curvature. It

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has been found that this model does not only avoid the causality problem and is phenomenologically viable, but also naturally solves the coincidence problem [17]. Feng and Li [18] discussed viscous RDE model by assuming that there is bulk viscosity in the linear barotropic fluid and the RDE. Lepe and Pena [19] studied the dark energy problem by adopting a holographic model by postulating an energy density $\rho \sim R$, where R is the Ricci scalar curvature and showed that the equation of state for the dark energy exhibits a cross through the -1 barrier. Feng [13] adopted a correspondence between the RDE model and a scalar field dark energy and reconstructed quintom from RDE. In another work, Feng [20] regarded the $f(R)$ theory as an effective description for the acceleration of the universe and reconstruct the function $f(R)$ from the RDE. State finder diagnostics of RDE was investigated by Feng [21].

The possibilities of an emergent universe [22] have been studied recently in a number of papers in which one looks for a universe which is ever-existing and large enough so that the spacetime may be treated as classical entities. In these models, the universe in the infinite past is in an almost static state but it eventually evolves into an inflationary stage [23]. An emergent universe model can be defined as a singularity free universe which is ever existing with an almost static nature in the infinite past ($t \rightarrow -\infty$) and then evolves into an inflationary stage [24]. Debnath [25] investigated the emergent universe scenario under the situation that the universe is filled with normal matter and phantom field or tachyonic field and derived various conditions for the possibility of the emergent universe in the flat, closed and open universes. Mukherjee et al [23] showed that the emergent universe scenarios are not isolated solutions and they may occur for different combinations of radiation and matter. Campo et al [26] studied the emergent universe model in the context of a self-interacting Jordan-Brans-Dicke theory and showed that the model presents a stable past eternal static solution which eventually enters a phase where the stability of this solution is broken leading to an inflationary period. Mukherjee et al [23] summarized the features of emergent universe as:

1. the universe is almost static at the finite past ($t \rightarrow -\infty$) and isotropic, homogeneous at large scales;
2. it is ever existing and there is no timelike singularity;
3. the universe is always large enough so that the classical description of space-time is adequate;
4. the universe may contain exotic matter so that the energy conditions may be violated;
5. the universe is accelerating as suggested by recent measurements of distances of high redshift type Ia supernovae.

A generalized model has been designed by Xu et al [27] to included HDE and RDE by introducing a new parameter which balances holographic and Ricci dark energy model. Xu et al [27] considered the energy densities for generalized holographic dark energy (GHDE) and generalized Ricci dark energy (GRDE) as

$$\rho_{GH} = 3c^2 M_{pl}^2 f\left(\frac{R}{H^2}\right) H^2 \quad (1)$$

$$\rho_{GR} = 3c^2 M_{pl}^2 g\left(\frac{H^2}{R}\right) R \quad (2)$$

where $f(x)$ and $g(y)$ are positive defined functions of the dimensionless variables $x = R/H^2$ and $y = H^2/R$ respectively. Xu et al (2009) had chosen

$$f\left(\frac{R}{H^2}\right) = 1 - \epsilon \left(1 - \frac{R}{H^2}\right) \quad (3)$$

$$g\left(\frac{H^2}{R}\right) = 1 - \eta \left(1 - \frac{H^2}{R}\right) \quad (4)$$

where ϵ and η are parameters. When $\epsilon = 0(\eta = 1)$ or $\epsilon = 1(\eta = 0)$, the generalized energy density becomes the holographic (Ricci) and Ricci (holographic) dark energy density respectively. If $\epsilon = 1 - \eta$, then GHDE and GRDE are equivalent.

One possibility to explain the current accelerated expansion of the universe may be related with the presence of cosmologically evolving scalar whose mass depends on the local matter density (chameleon cosmology) [28]. In the flat homogeneous universe the action of chameleon field [29] is given by [30]

$$S = \int \sqrt{-g} d^4x \left[f(\phi) \mathcal{L} + \frac{1}{2} \phi_{,\mu} \phi^{,\mu} + \frac{R}{16\pi G} - V(\phi) \right] \quad (5)$$

where ϕ is the Chameleon scalar field and $V(\phi)$ is the Chameleon potential. Also, R is the Ricci scalar and G is the Newtonian constant of gravity, $f(\phi) \mathcal{L}$ is the modified matter Lagrangian and $f(\phi)$ is an analytic function of ϕ . This term brings about the non-minimal interaction between the cold dark matter and Chameleon field. Reason behind dubbing the scalar field as ‘‘Chamelion’’ is stated in Khoury and Weltman [29] as: ‘‘We refer to ϕ as a ‘chameleon’ field, since its physical properties, such as its mass, depend sensitively on the environment. Moreover, in regions of high density, the chameleon ‘blends’ with its environment and becomes essentially invisible to searches for equivalence principle violation and fifth force’’.

In the present paper we have considered emergent scenario of the universe in presence of GRDE with chameleon field. Following references [23] and [24] the scale factor has been taken in the form

$$a = a_0 (\beta + e^{\alpha t})^n \quad (6)$$

where the constant parameters are restricted as follows [24]:

1. $a_0 > 0$ for the scale factor a to be positive,
2. $\beta > 0$, to avoid any singularity at finite time (big-rip),
3. $\alpha > 0$ or $n > 0$ for expanding model of the universe,
4. $\alpha < 0$ and $n < 0$ implies big bang singularity at $t = -\infty$.

B. RDE in emergent universe

In this section we are beginning with Ricci dark energy (RDE) which is characterized by the energy density [16, 27]

$$\rho_R = 3c^2 \left(\dot{H} + 2H^2 + \frac{k}{a^2} \right) \quad (7)$$

where c is a dimensionless parameter which will determine the evolution behavior of RDE. When $c^2 < 1/2$, the RDE will exhibit a quintomlike behavior; i.e., its equation of state will evolve across the cosmological-constant boundary $w = -1$. Reviews on RDE are available in papers like [27], [31], [32] and [33]. The conservation equations for RDE is

$$\dot{\rho}_R + 3H(\rho_R + p_R) = 0 \quad (8)$$

In a flat universe i.e. $k = 0$, we have $\rho_R = 3c^2(\dot{H} + 2H^2)$. Solving the conservation equation for RDE in a flat universe one can obtain the pressure as

$$p_R = -c^2 \left(\frac{\ddot{H}}{H} + 7\dot{H} + 6H^2 \right) \quad (9)$$

With the choice of scale factor for emergent universe we obtain the equation of state (EOS) parameter $w_{RDE} = p_{RDE}/\rho_{RDE}$ and plot it in figure 1, which shows that the EOS parameter is staying below -1 and

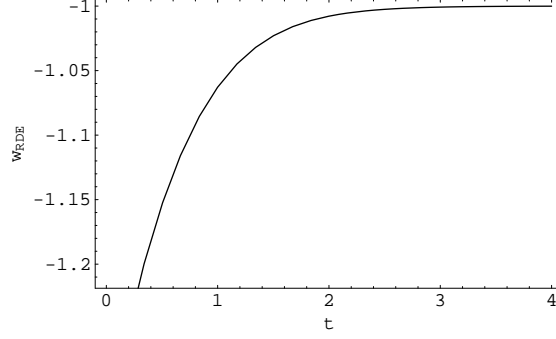


Fig.1

Fig. 1 shows the EOS parameter w_{RDE} for RDE under emergent universe. The EOS parameter $w_{RDE} < -1$, which indicates phantom like behaviour.

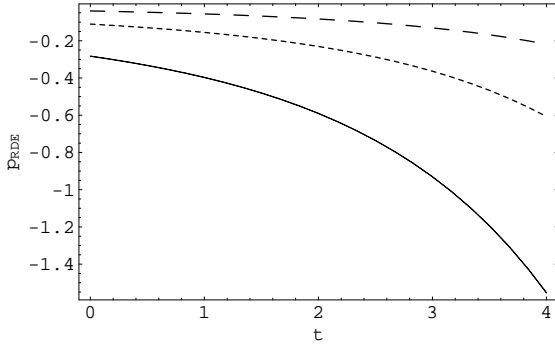


Fig.2

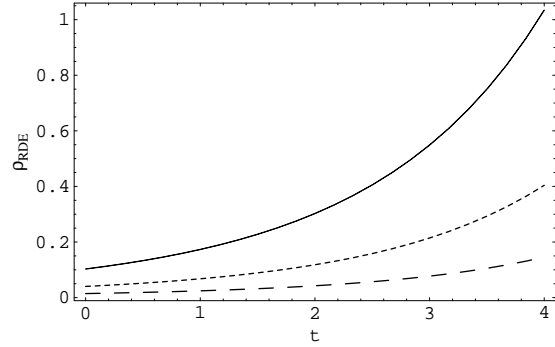


Fig.3

Fig.2 and 3 represent the pressure and energy density of RDE under emergent universe for $c = 0.8$ (thick line), 0.5 (dotted line) and 0.3 (broken line).

gradually tending to -1 with passage of cosmic time. Thus, we find that the RDE is behaving like phantom in emergent universe.

The pressure and energy density parameters plotted in figures 2 and 3 show that the negative pressure is falling and energy density is increasing with passage of cosmic time. In the next section we shall switch over to the generalized situation in emergent universe scenario.

c. GRDE in emergent universe

Issues associated with GRDE are already discussed in Section I. In the case of GRDE, using equations (2) and (4) the Friedman's equation is

$$H^2 = \frac{1}{3M_{pl}^2}(\rho_m + \rho_{GR}) = H^2\Omega_m + c^2 \left[1 - \eta \left(1 - \frac{H^2}{R} \right) \right] R \quad (10)$$

where $\Omega_m = \frac{\rho_m}{3M_{pl}^2 H^2}$ is the energy density for dark matter. In the emergent scenario, the energy density for GRDE is found to be

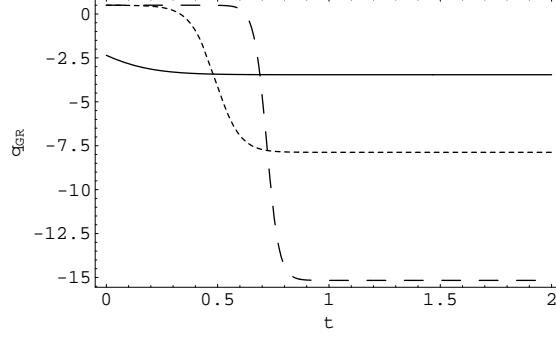


Fig.4

Fig. 4 shows the deceleration parameter q_{GR} for GRDE under emergent universe. The negative sign of q_{GR} shows the ever accelerating universe under emergent universe. ($\eta = 1/3$; $c = 0.8, 0.5, 0.3$; $H_0 = 72$)

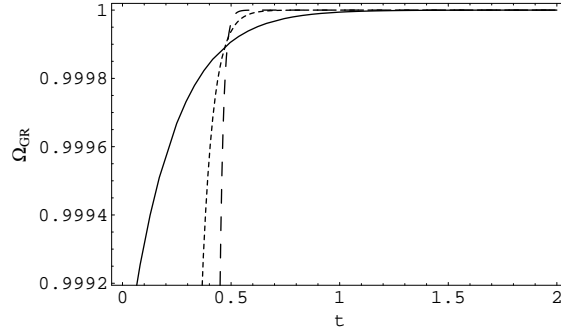


Fig.5

Fig. 5 shows the fractional energy density Ω_{GR} of GRDE under emergent universe. The increasing behaviour of Ω_{GR} with cosmic time t reflects the dark energy dominated universe. ($\eta = 1/3$; $c = 0.8, 0.5, 0.3$; $H_0 = 72$)

$$\Omega_{GR} = c^2[2 - \eta + \frac{H_0^2 a_0 (e^{t\alpha} + \beta)^n (1 + c^2(-2 + \eta))(-2 + c^2(1 + \eta) + 2\Omega_{m0})}{c^2 \left(-2 \left(\frac{e^{\alpha t} + \beta}{a_0} \right)^{-n} \frac{2(-1 + c^2)}{c^2(-1 + \eta)} \Omega_{m0} + H_0^2 (e^{\alpha t} + \beta)^n a_0 (-2 + c^2(1 + \eta) + 2\Omega_{m0}) \right)} + \frac{3(-1 + \eta)\Omega_{m0}}{2\Omega_{m0} - H_0^2 \left(\frac{e^{\alpha t} + \beta}{a_0} \right)^{-1 - \frac{2(-1 + c^2)}{c^2(-1 + \eta)}}} (-2 + c^2(1 + \eta) + 2\Omega_{m0})] \quad (11)$$

Deceleration parameter is computed as

$$q_{GR} = \frac{1}{1 - \eta} - \frac{\Omega_{GR}}{c^2(1 - \eta)} \quad (12)$$

The deceleration and energy density parameters are plotted in figures 4 and 5.

From the negative deceleration parameter throughout the evolution of the universe the ever accelerating nature of the emergent universe is reflected. The energy density Ω_{GR} in figure 5 gradually increases with cosmic time and tends to 1. This indicates the dark energy dominated universe. From figure 6, which depicts the EOS parameter w_{GR} , it is apparent that the EOS parameter is < -1 . This indicates phantom like behaviour of the GRDE in the emergent universe scenario. In all these plots we have taken $\eta = 1/3$. We know from reference [27] that if we take $\epsilon = 1 - 1/3 = 2/3$ in equation (3) and then use it in equation (1) then we get a GHDE

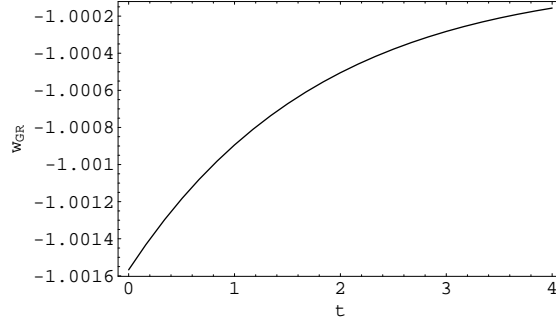


Fig.6

Fig. 6 shows the EOS parameter w_{GR} for GRDE under emergent universe. The $w_{GR} < -1$ reflects the phantom like behaviour. ($\eta = 1/3; H_0 = 72$)

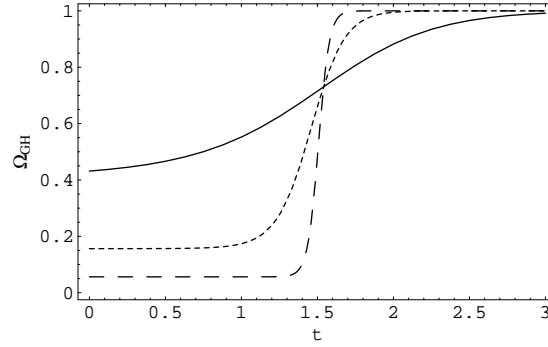


Fig.7

Fig. 7 shows the the fractional energy density Ω_{GH} of GHDE under emergent universe. The increasing behaviour of Ω_{GH} with cosmic time t reflects the dark energy dominated universe. ($\epsilon = 3/4; c = 0.8, 0.5, 0.3; H_0 = 72$)

equivalent to the GRDE discussed above. To get a different GHDE we take $\epsilon = 3/4$. We obtain the energy density Ω_{GH} and deceleration parameter q_{GH} for the GHDE in emergent universe as follows

$$\Omega_{GH} = (1+\epsilon)c^2 + \frac{-1 + c^2(1+\epsilon)}{\left(-1 - \frac{2(\frac{e^{t\alpha} + \beta)^{-n}}{a_0})^{1+\frac{-2+\frac{2}{\epsilon}}}{2+c^2(-2+\epsilon)-2\Omega_{m0}}}\Omega_{m0}\right)} + \frac{3c^2\epsilon\Omega_{m0}}{-2\Omega_{m0} + (\frac{e^{t\alpha} + \beta)^{-n}}{a_0})^{-1+\frac{2-\frac{2}{\epsilon}}{\epsilon}}(-2 - c^2(-2 - c^2(-2+\epsilon) + 2\Omega_{m0}))} \quad (13)$$

$$q_{GH} = \frac{1}{\epsilon} - \frac{\Omega_{GH}}{c^2\epsilon} \quad (14)$$

The energy density and deceleration parameters are plotted in figures 7 and 8 respectively. Like GRDE, here also we find a gradually increasing energy density and a deceleration parameter which is always negative. This means that we are getting an ever accelerating universe under emergent scenario with GHDE. The phantom like behaviour of the EOS parameter of GHDE in emergent universe scenario is apparent from figure 9. This behaviour is similar to that of GRDE. In the subsequent section we would describe the role of GRDE on Chameleon field in the emergent universe.

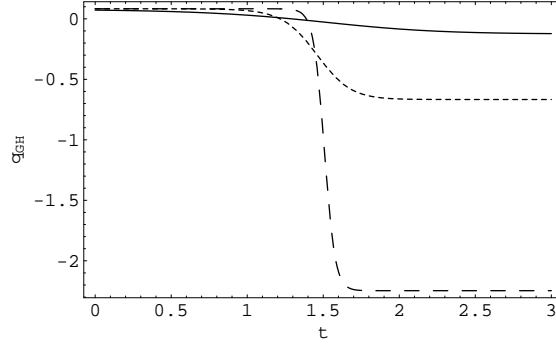


Fig.8

Fig. 8 shows the deceleration parameter q_{GH} for GHDE under emergent universe. ($\epsilon = 3/4$; $c = 0.8, 0.5, 0.3$; $H_0 = 72$)

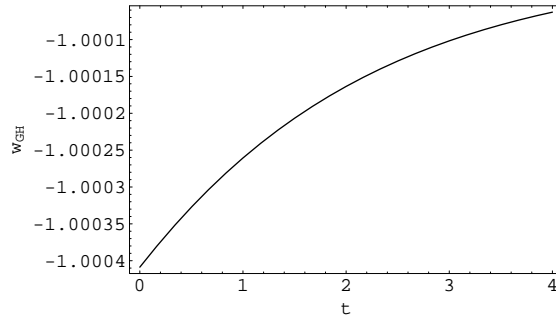


Fig.9

Fig. 9 shows the EOS parameter w_{GH} for GHDE under emergent universe. The $w_{GH} < -1$ reflects the phantom like behaviour. ($\epsilon = 3/4$; $H_0 = 72$)

D. GRDE on chameleon field

The variation of action (5) with respect to the metric tensor components in a FRW cosmology yields

$$3H\dot{\phi} + \ddot{\phi} + \frac{dV}{d\phi} + (\rho + p)\frac{df}{d\phi} = 0 \quad (15)$$

which reduces to

$$3H\dot{\phi}^2 + \dot{\phi}\ddot{\phi} + \dot{V} + (p + \rho)\dot{f} = 0 \quad (16)$$

which is the wave equation for the chameleon field. Again, the variation of the same equation with respect to metric tensor components gives (choosing $8\pi G = 1$)

$$3\frac{\dot{a}^2}{a^2} = \rho f + \frac{1}{2}\dot{\phi}^2 + V(\phi) \quad (17)$$

$$2\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2} = -pf - \frac{1}{2}\dot{\phi}^2 + V(\phi) \quad (18)$$

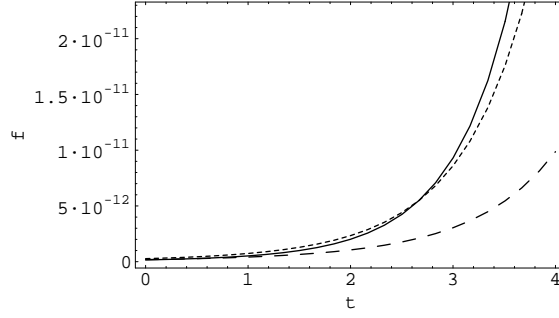


Fig.10

Fig. 10 shows that f increases with cosmic time t . We have taken $\eta = 1/3$; $c = 0.8, 0.5, 0.3$.

Following reference [34] we choose

$$V = V_0 \phi^2 \quad (19)$$

From the equations (17) and (18) we get

$$\frac{d}{dt}(\rho f) + 3H(p + \rho)f = (p + \rho)\dot{f} \quad (20)$$

As we are considering the GRDE in the emergent universe, we replace ρ by $\rho_{GR} = 3c^2 M_{pl}^2 (1 - \eta(1 - \frac{H^2}{R}))R$. Eliminating $\dot{\phi}^2$ from the field equations and using the form of p in equation (20) with $H = \frac{e^{t\alpha} n \alpha}{e^{t\alpha} + \beta}$ we get (taking $M_{pl} = 1$)

$$\xi_1(t) = \frac{e^{t\alpha} n \alpha^2 [a(3ne^{t\alpha} + 2\beta) - 3b(6c^2\beta(-1 + \eta) + e^{t\alpha}n(-1 + c^2(-12 + 3\eta)))]}{(e^{t\alpha} + \beta)^2} \quad (21)$$

$$\begin{aligned} \xi_2(t) = & -\frac{1}{(e^{t\alpha} + \beta)^4} [3e^{2t\alpha} n^2 \alpha^3 (3b(e^{t\alpha} + \beta)(6c^2\beta(-1 + \eta) + ne^{t\alpha}(-1 + c^2(-12 + 13\eta))) \\ & + a(2\beta^2(-1 + 9c^2(1 + \alpha)(-1 + \eta)) + 3ne^{2t\alpha}(-1 + c^2(-12 + 13\eta)) \\ & + e^{t\alpha}\beta(-2 - 3n + 3c^2(n(1 + 2\alpha)(-12 + 13\eta) + 6(-1 + \eta)(1 - \alpha)))))] \end{aligned} \quad (22)$$

where $a = V_0 + \frac{1}{2}$ and $b = V_0 - \frac{1}{2}$ and consequently f is reconstructed as

$$f = f_0 \left[\exp \int \frac{\xi_2(t)}{\xi_1(t)} dt \right] \quad (23)$$

Now, f is plotted against cosmic time t in figure 10, which shows that f is increasing with cosmic time t .

As we know the forms of H , f and ρ_{GR} , we obtain the the chameleon scalar field ϕ from equation (17) and consequently the potential V is obtained.

It is observed in the figures 11 and 12 that the chameleon scalar field ϕ and potential V are increasing with cosmic time in presence of GRDE in emergent universe scenario. In figures 13 and 14 we have plotted V and f both of which are functions of the chameleon scalar field ϕ . It is observed from the above figure that both are increasing functions of ϕ in presence of GRDE in emergent universe scenario. However, V has a sharper increase than f with increase in the chameleon scalar field ϕ .

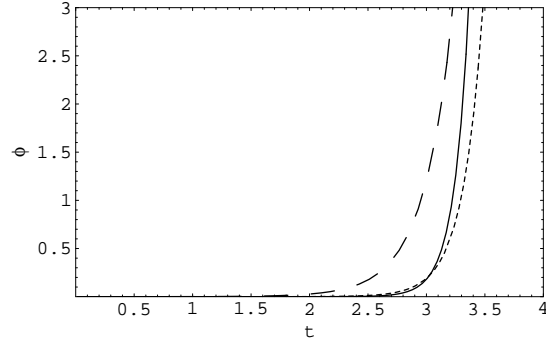


Fig.11

Fig. 11 shows the increasing chameleon scalar field ϕ in presence of GRDE in emergent universe scenario. We have taken $\eta = 1/3$; $c = 0.8, 0.5, 0.3$.

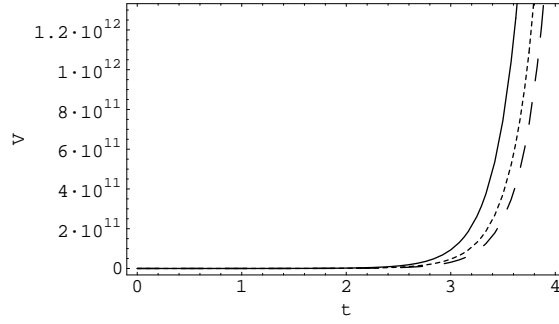


Fig.12

Fig. 12 shows the increasing potential V of the chameleon field in presence of GRDE in emergent universe scenario. We have taken $\eta = 1/3$; $c = 0.8, 0.5, 0.3$.

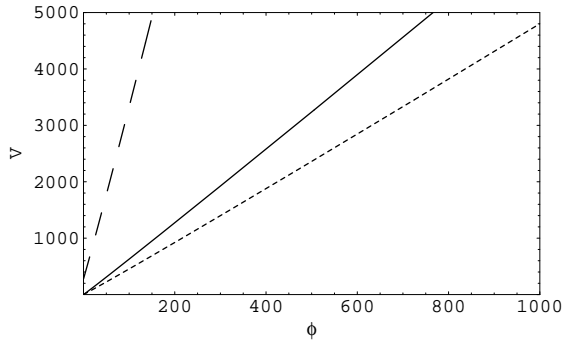


Fig.13

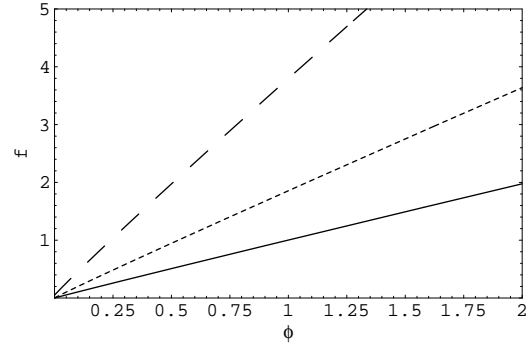


Fig.14

Fig. 13 shows the evolution of the potential V with chameleon scalar field ϕ and Fig. 14 shows evolution of the analytic function f with chameleon scalar field ϕ . We have taken $\eta = 1/3$; $c = 0.8, 0.5, 0.3$.

E. Concluding remarks

In this paper, generalized Ricci dark energy model, proposed by Xu et al [27], is presented, where the energy density is given by $\rho_{GR} = 3c^2 M_{pl}^2 g\left(\frac{H^2}{R}\right) R$. This generalized form is considered in the emergent universe scenario. At the beginning of the study, we considered the Ricci dark energy with energy density $\rho_R = 3c^2 \left(\dot{H} + 2H^2 + \frac{k}{a^2}\right)$ in the emergent universe scenario. The most powerful quantity of dark energy is its equation-of-state w . If we restrict ourselves in four-dimensional Einstein's gravity, nearly all dark energy models can be classified by the behaviors of equations of state as following [35]: (i) for cosmological constant $w = -1$, (ii) for quintessence $w > -1$, (iii) for phantom $w < -1$ (iv) for quintom w crosses the boundary of -1 . To discern the behavior of the Ricci dark energy model we considered in this work, we computed the equation of state parameter w under different situations. In the case of ordinary Ricci dark energy we found (fig. 1) that w is below -1 at early stages of the universe and at later stages it is tending to -1 . However, it is not crossing the boundary of -1 . This means that under emergent universe scenario the equation of state parameter of Ricci dark energy behaves like phantom. This observation is in contrast with the observation of reference [16], where the authors found the crossing of -1 boundary by w . However, in this work, we have considered emergent scenario that was not there in [16]. The negative pressure p is gradually decaying (fig. 2) and dark energy density is gradually increasing with cosmic time t in this situation. Next we considered the generalized Ricci dark energy in the emergent universe scenario and plotted the deceleration parameter q and fractional energy density Ω against cosmic time t for $c = 0.8, 0.5$ and 0.3 . We observed that q is staying a negative level throughout the evolution of the universe (fig. 4). This is consistent with the emergent (i.e. ever accelerating) universe. The fractional energy density (fig. 5) is plotted against cosmic time and it is found that the fractional energy density is increasing and gradually tending to 1. This observation is consistent with the dark energy dominated universe. Simultaneously we have observed the behaviour of generalized Holographic dark energy proposed in [27] and observed similar behaviours in the deceleration parameter and fractional energy density (figs. 7 and 8). Also, we derived the equation of state parameters and for generalized Ricci (fig. 6) as well as generalized holographic dark energy (fig. 9) and we found that in both of the cases they are behaving like phantom (i.e. $w < -1$). Finally we considered the chameleon field and examined the behaviours of the chameleon scalar field, potential and the associated function f in presence of generalized Ricci dark energy in emergent universe scenario for $c = 0.8, 0.5, 0.3$ and $\eta = 1/3$. In fig. 10 we plotted the function f and observed its increasing behaviour with cosmic time. The chameleon scalar field and potentials, plotted in figs. 11 and 12 exhibit increasing pattern with cosmic time. It was further noted from figs. 13 and 14 that among V and f , the potential V has a sharper increase with the chameleon scalar field than that of f in the situation under consideration.

In summary, it may be noted that the equation of state parameter for generalized Ricci dark energy is always exhibiting phantom like behavior under emergent scenario of the universe. It is already observed from the behavior of the deceleration parameter that the universe is highly accelerated under the emergent scenario. Because of this highly accelerated expansion, the equation of state parameter is remaining at the phantom phase and is not crossing the -1 boundary.

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